STATE OF FLORIDA
DEPARTMENT OF NATURAL RESOURCES
Randolph Hodges, *Executive Director*

DIVISION OF INTERIOR RESOURCES
Robert O. Vernon, *Director*

BUREAU OF GEOLOGY
Charles W. Hendry, Jr., *Chief*

INFORMATION CIRCULAR NO. 77

GROUND WATER IN THE HALLANDALE AREA, FLORIDA

By
H. W. Bearden

Prepared by the
UNITED STATES GEOLOGICAL SURVEY
in cooperation with the
CITY OF HALLANDALE
and the
BUREAU OF GEOLOGY
FLORIDA DEPARTMENT OF NATURAL RESOURCES

TALLAHASSEE
1972

DEPARTMENT OF NATURAL RESOURCES

REUBIN O'D. ASKEW
Governor

RICHARD (DICK) STONE
Secretary of State

ROBERT L. SHEVIN
Attorney General

THOMAS D. O'MALLEY
Treasurer

FRED O. DICKINSON, JR.
Comptroller

FLOYD T. CHRISTIAN
Commissioner of Education

DOYLE CONNER
Commissioner of Agriculture

W. RANDOLPH HODGES
Executive Director

LETTER OF TRANSMITTAL

Bureau of Geology
Tallahassee
September 29, 1972

Honorable Reubin O'D. Askew, Chairman
Department of Natural Resources
Tallahassee, Florida

Dear Governor Askew:

The water problems confronting Hallandale are similar to those of other coastal cities of southeastern Florida which are undergoing rapid growth with tremendous increase in water demand. The highly permeable Biscayne aquifer underlying the Hallandale area is an excellent source of water; however, the permeable nature of the Biscayne aquifer would permit the intrusion of sea water, if fresh water levels were lowered excessively, as well as the infiltration of urban or industrial contaminants, from land surfaces and surface water bodies.

This study is to provide the hydrologic data necessary for proper water resource development and planning in the Hallandale area.

Respectfully yours,

C. W. Hendry, Jr.
Bureau Chief
State Geologist

Completed manuscript received
February 1, 1972
Printed for the Florida Department of Natural Resources
Division of Interior Resources
Bureau of Geology
by News-Journal Corporation
Daytona Beach, Florida

Tallahassee
1972

CONTENTS

ILLUSTRATIONS

TABLES

GROUND WATER IN THE HALLANDALE AREA, FLORIDA

By
H. W. Bearden
U. S. Geological Survey

ABSTRACT

Fresh ground water for all purposes in Hallandale is provided by the highly permeable Biscayne aquifer. The aquifer is composed chiefly of permeable limestone, sandstone, and sand that extends from land surface to a depth of approximately 200 feet. The major source of recharge to the aquifer is rain that falls on the area and infiltrates to the water table. The aquifer is also being recharged by Snake Creek Canal during dry periods.

The configuration of the water table in Hallandale is greatly influenced by the Intracoastal Waterway, the Oleta River, Snake Creek Canal, and municipal pumping.

Large quantities of water are available from the Biscayne aquifer in Hallandale. The aquifer is similar in character to the aquifer in the vicinity of the well fields in the city of North Miami Beach, where transmissivity ranges from 2.0 to 2.5 million gallons per day per foot.

The chemical quality of the ground-water is generally good except in areas of sea-water intrusion. The inland extent of this intrusion at the base of the aquifer has been detected 0.3 mile east of the well field. The well field is 2 miles west of the Intracoastal Waterway, the closest source of sea-water intrusion. Developing new, additional supplies in the southwest part of Hallandale would safeguard the aquifer against salt-water intrusion.

INTRODUCTION

The water problems confronting Hallandale are similar to those of other coastal cities of southeastern Florida, which are undergoing mushrooming growth and rapid increases in water demand. The highly permeable Biscayne aquifer underlying the Hallandale area is an excellent source of water. However, the permeable nature of the Biscayne aquifer would permit the inland intrustion of sea water, if fresh-water levels were lowered excessively, as well as the infiltration of urban or industrial contaminants from land surfaces and surface-water bodies. The present water supply is adequate, but additional supplies will be required to meet future demands. Recognizing the need for hydrologic data to aid in solving their water problems, the city of Hallandale requested, in 1969, that the U.S. Geological Survey study the water resources of the Hallandale area.

PURPOSE AND SCOPE

The purpose of this report is to present a summary of the shallow ground-water resources of the Hallandale area to provide information for future development of water supplies and to aid in safeguarding water supplies from contamination by sea water and by man-made wastes. This information was obtained by determining the following: (1) the availability and chemical quality of water in the Biscayne aquifer, (2) the general direction of ground water movement, (3) the occurrence and extent of sea-water intrusion, and (4) the chemical quality of water in borrow pits in the area.

This report was prepared by the U.S. Geological Survey in cooperation with the city of Hallandale and as a part of the statewide program with the Bureau of Geology, Florida Department of Natural Resources. The fieldwork and report preparation were under the immediate supervision of C. B. Sherwood, Project Engineer and T. J. Buchanan, Subdistrict Chief, Miami, Florida, and under the general supervision of C. S. Conover, district chief, Tallahassee, Florida, all of the U.S. Geological Survey.

PREVIOUS INVESTIGATIONS

General information on the hydrology and geology of the area has been published in reports by Cooke and Mossom (1929), Parker and Cooke (1944), Cooke and Parker (1945), and Parker and others (1955). Additional information on the area is included in reports from investigations in Broward County and North Dade County by Sherwood (1959), Leach and Sherwood (1963), Tarver (1964), Sherwood and Grantham (1965), Grantham and Sherwood (1968), and McCoy and Hardee (1970). The present report is the first to supply detailed information of the ground-water resources of the Hallandale area.

ACKNOWLEDGMENTS

Special appreciation is expressed to Mr. R. F. Williams, City Manager of Hallandale, and all the Hallandale officials for their cooperation during

the investigation; to Mr. Ralph Diseca, and Mr. John Layne, past and present water-treatment-plant superintendents, for information about the Hallandale water supply; to the residents of Hallandale who furnished information about their wells; and to the consulting firm of Ross, Saarinen, Boulton, and Wilder for its assistance in providing information on the city's water-supply system.

GENERAL FEATURES

The area of study is the city of Hallandale, an area of about 4 square miles in southeastern Florida. Hallandale is bounded by the ocean on the east, highly urbanized Dade and Broward County areas on the south and west, respectively, and the city of Hollywood on the north. The Intracoastal Waterway divides Hallandale's beach area from the rest of the city.

Hallandale's population increased 133 percent from 10,480 in 1960 to 24,440 in 1970. Many of the new residents are housed in high-rise apartments and condominiums. Many of the permanent residents in Hallandale are retirees.

Tourism accounts for a major part of the economy. Hallandale's ideal location, excellent beaches, access to major attractions in southeastern Florida make it an ideal resort for many winter visitors.

CLIMATE

The climate of Hallandale is subtropical and characterized by long warm, humid summers and mild winters. The average monthly temperature at

Table 1. Average monthly rainfall and average monthly temperature at Fort Lauderdale, Florida, 1913-69. [1]

Month	Fort Lauderdale Rainfall (Inches)	Fort Lauderdale Temperature (°F.)
January	2.20	67.8
February	2.06	68.4
March	2.84	70.7
April	4.19	74.3
May	5.29	77.5
June	7.42	80.4
July	5.96	81.8
August	6.88	82.6
September	8.98	81.5
October	8.39	77.9
November	3.18	72.6
December	2.90	69.0
Yearly Average	60.29	75.4

[1] Record from U.S. Weather Service's Climatological Data.

Fort Lauderdale, 8 miles north of Hallandale, 1913-69, ranged from 67.8° F. in January to 82.6° F. in August. The average annual temperature for that period was 75.4° F. The average annual rainfall at Fort Lauderdale for the period was 60.3 inches, of which 71 percent fell during May-October, as shown in table 1.

HYDROLOGIC SETTING

The Hallandale area is on the coastal ridge that separates the ocean from the Everglades. The ridge is about 6 miles wide and nearly everywhere is very low and flat. The ridge crests about 2 miles inland, and Hallandale's western boundary is about 3 miles inland. The land surface in Hallandale ranges in altitude from 5 to 10 feet and averages about 7 feet.

No major canals are within the area, and, consequently, surface drainage is slight. Most of the drainage is underground, to the ocean, and to the Oleta River and Snake Creek Canal south of the area.

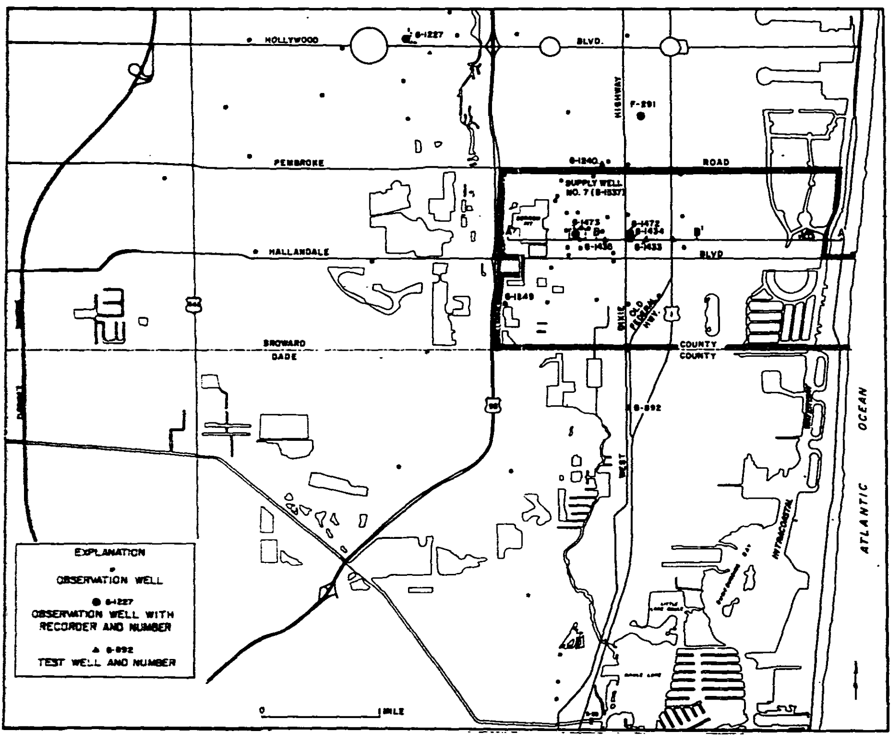

Figure 1. Locations of observation wells and line of geologic section.

BISCAYNE AQUIFER

The Hallandale area, all the coastal areas, and most of the Everglades in Broward County are underlain by the Biscayne aquifer (Schroeder and others, 1958). Fresh water supplies for all purposes in the Hallandale area are derived from the Biscayne aquifer. The aquifer extends from land surface to a depth of about 200 feet in the area and is underlain by massive beds of marine sediments and marl of low permeability. These beds extend to a depth of about 900 feet and separate the Biscayne aquifer from the deep Floridan aquifer.

The Biscayne aquifer is composed chiefly of permeable beds of limestone, sandstone, and sand that range in age from late Miocene through Pleistocene (Tarver, 1964, p. 7). In Hallandale, the aquifer is composed of the following marine Pleistocene formations (in sequence from oldest to youngest), Anastasia Formation, Miami Oolite, and Pamlico Sand.

Four test wells, G-1432, G-1433, G-1434, and G-1435, were drilled on an east-west line in Hallandale, as shown in figure 1. The wells range in depth from 110 to 204 feet. The logs from these wells were used to construct a geologic section of the aquifer, as shown in figure 2.

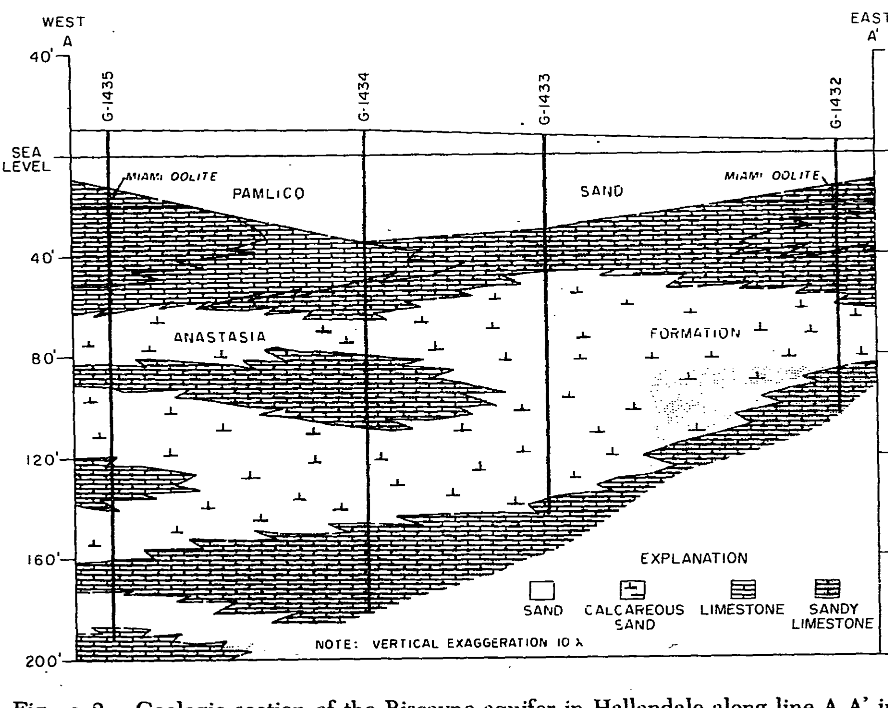

Figure 2. Geologic section of the Biscayne aquifer in Hallandale along line A-A' in figure 1.

The Pamlico Sand, which blankets most of the Hallandale area, is generally 20 to 50 feet thick (fig. 2). The Pamlico Sand is a late Pleistocene terrace deposit of marine origin. Parker and Cooke (1945) extended the range of the Pamlico Sand from North Carolina into Florida and defined it to include all the marine Pleistocene deposits younger than the Anastasia Formation. The Pamlico Sand is chiefly a quartz sand ranging in color from light gray or white to red and gray-black, depending on the amount of incorporated iron oxide or carbonaceous material (Schroeder and others, 1958 p. 24). The sand ranges from very fine to coarse and where coarse, yields small amounts of fresh water to wells.

The Miami Oolite was named by Sanford (1909, p. 211-214) and redefined by Cooke and Mossom (1929, p. 204-207) to include all the oolitic limestone of southern Florida. Where it exists, the Miami Oolite underlies the Pamlico Sand at depths from sea level to not more than 20 feet below sea level. Oolite was penetrated during the drilling of the test wells, and the approximate extent of the formation in the geologic section A-A' is shown in figure 2. The Miami Oolite is typically a white to yellowish soft chalky oolitic limestone containing varying amounts of sand. Where the oolite occurs in thick continuous layers, it is a good source of water, but, because it is thin and discontinuous in most areas, very little water is obtained from it.

The Anastasia Formation of Pleistocene age underlies the Pamlico Sand and Miami Oolite. It is the major source of fresh water and represents the chief component of the Biscayne aquifer in the Hallandale area. The formation is composed of coquina, sand, calcareous sand, limestone, and sandy limestone. The limestone and sandy limestone beds are very permeable and will yield large amounts of water. The limestone beds vary in depth and are discontinuous vertically and horizontally (fig. 2).

GROUND WATER

Ground water is the subsurface water in the zone of saturation, the zone in which all voids, large and small, are (ideally) filled with water under pressures greater than atmospheric. The subsurface formations containing water, and from which water is available for use, are called aquifers (Meinzer, 1923, p. 38-39). Water may occur in aquifers under either artesian or nonartesian conditions. Where the upper surface of the water is free to rise and fall in a permeable stratum it is said to be under nonartesian conditions, and the surface is called the water table. Water confined under pressure is said to be under artesian conditions.

The water table is an undulating surface conforming generally to the topography. The water table is in contact with the atmosphere and is marked approximately by the level at which water stands in wells. The water table fluctuates in response to recharge or discharge, and ground water moves downgradient from areas of recharge, where levels are high, to areas of discharge, where levels are low. The water table can be mapped (contoured) by determining the altitude of the water table in a network of wells. Water-table maps show the shape and slope of the water table and the general direction of ground-water movement.

In general the Biscayne aquifer is nonartesian, but in the Hallandale area it is partly confined by discontinuous layers of less permeable materials.

RECHARGE AND DISCHARGE

Although the major source of fresh-water recharge to the Biscayne aquifer in Hallandale is rainfall, less than half the annual rainfall infiltrates to the water table. The remainder is evaporated, used by plants, or runs off into canals and the ocean. Water that reaches the water table is discharged from the aquifer by evapotranspiration, by outflow to the canals and the ocean, and by pumping from wells. Discharge by evapotranspiration and ground-water outflow represent major losses from the aquifer. They are greatest when water levels in the aquifer are high. Discharge by pumping from wells represents a small loss; is greatest during the dry season when water levels in the aquifer are low. An average of 3.36 mgd (million gallons per day) was pumped from the Hallandale municipal wells in 1970.

There is little surface-water recharge to the Biscayne aquifer in the Hallandale area except from the Snake Creek Canal during the dry season, when the water in Snake Creek Canal is maintained at higher levels than the adjacent ground-water levels. Then, the direction of ground-water flow is from Snake Creek Canal north to Hallandale. During the rainy season ground water flows south to the Oleta River and Snake Creek Canal and east to the Intracoastal Waterway.

WATER-LEVEL FLUCTUATIONS

Water-level fluctuations in the Biscayne aquifer in Hallandale are caused by variations in the amount of recharge and discharge. Rapid short-term fluctuations are the result of recharge by rainfall and discharge by pumping. Gradual changes in water levels are the result of the interplay of evapotranspiration and normal ground-water outflow, on the one hand, and of recharge in fluctuating amount on the other. Variations in rainfall are the major cause of water-level fluctuation in wells in Hallandale that tap the Biscayne.

Hydrographs for well G-1472 and G-1473 and a bar graph of daily

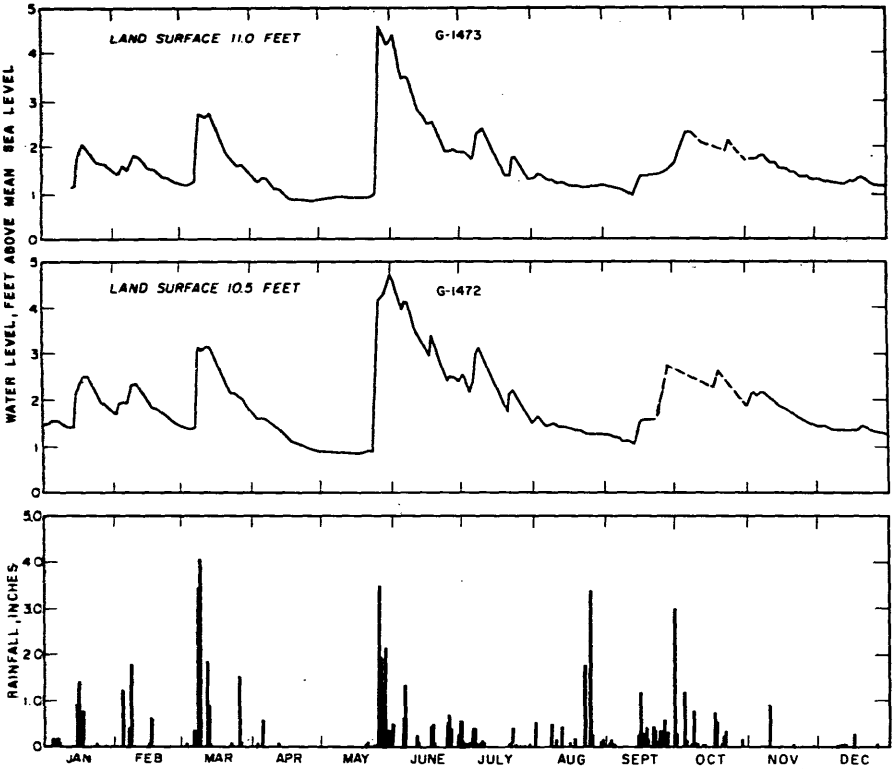

Figure 3. Water levels in wells G-1472 and G-1473 and daily rainfall at Fort Lauderdale, for 1970.

rainfall at Fort Lauderdale for 1970 are shown in figure 3. Rapid rises in water levels shown in these graphs are caused by recharge from rainfall, and show immediate response of the aquifer to such recharge. Water-level recessions are gradual and are caused by evapotranspiration and ground-water outflow.

Well G-1472, about 20 feet deep, is 0.4 mile directly east of the well field (fig. 1). The water-level in the well is not influenced by well-field withdrawal and, hence, is representative of the regional water table.

Well G-1473 is a test well drilled 130 feet deep in the well field for sampling to determine the quality of water below the depth of the municipal wells, which range from 65 to 100 feet deep. Water-level fluctuations and response to rainfall in this well are similar to those of well G-1472. Although well G-1473 is in the center of the well field and well G-1472 is 0.4 mile east of the well field, there is no marked difference in the hydrograph of the two, other than the slightly lower levels in well G-1473. To observe water levels in the zone from which the municipal wells are pumped, an observation well, G-1473A, was drilled 5 feet north of well G-1473 to a depth of 96 feet. A hydrograph of well G-1473A and the daily pumping rate from the well field March 13-19, 1971, are shown in figure 4. The

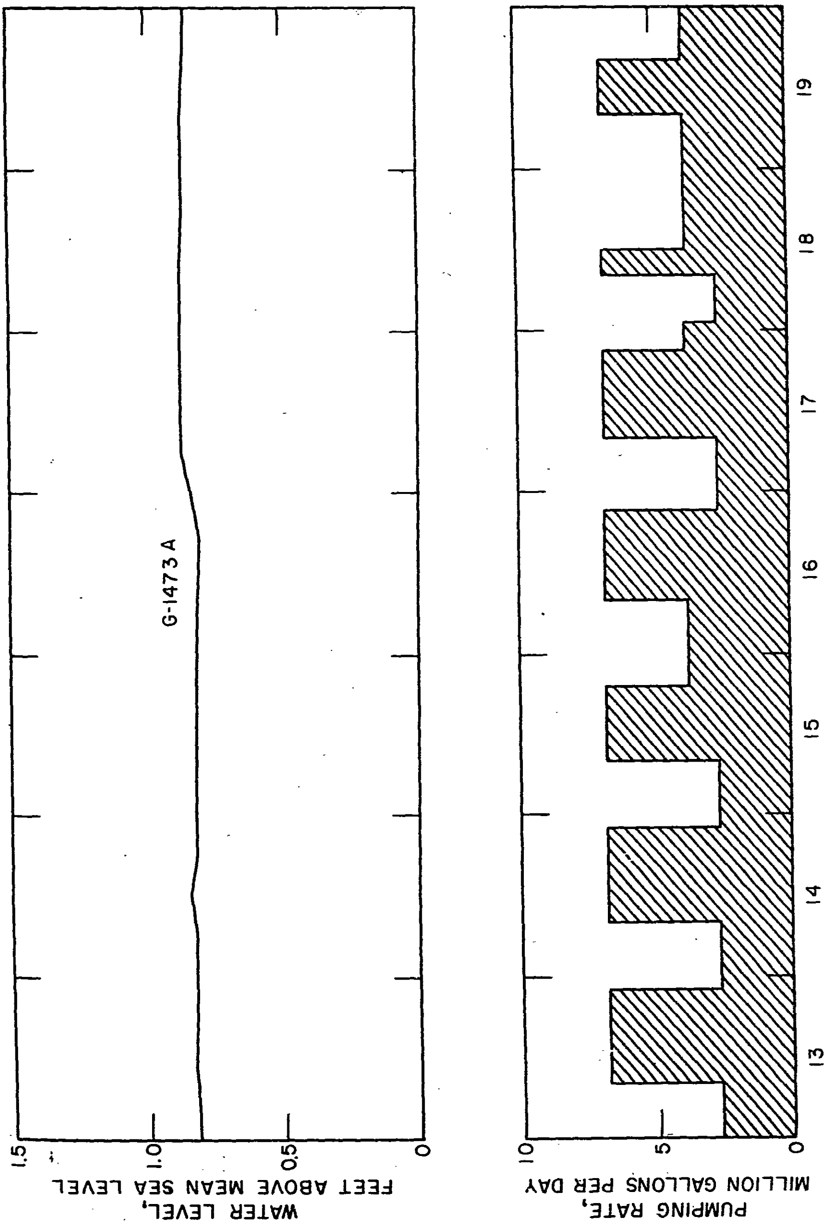

Figure 4. Water level in well G-1473A and the pumpage rate from the Hallandale well field for March 13-19, 1971.

hydrograph shows only minute changes in water levels in the aquifer when changes in withdrawal rates from the well field were substantial, indicating that well field pumping has little effect on the water table and also that the aquifer is highly permeable and will transmit large volumes of water.

A study of the configuration and fluctuation of the water table in Hallandale was made from water levels measured periodically in a network of wells shown in figure 1. Water-levels measured in these wells during high and low water levels in the aquifer were used to prepare water-table con-

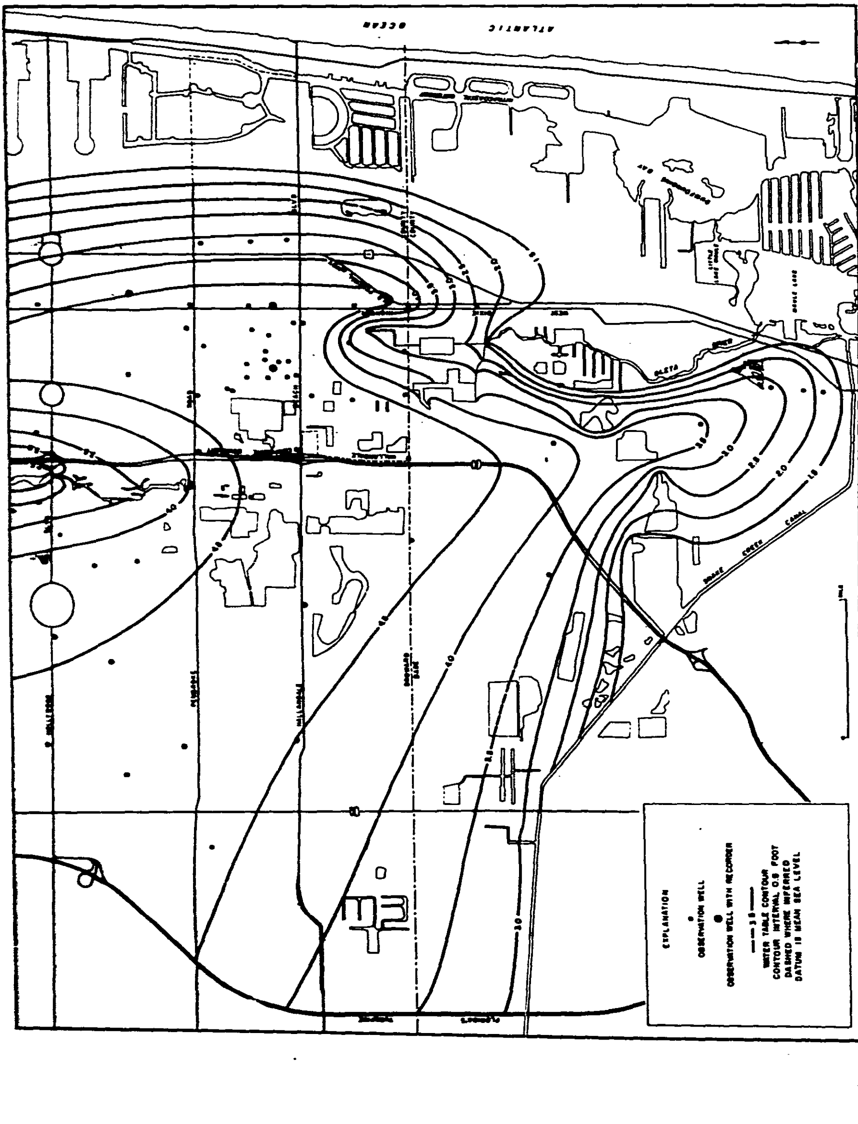

Figure 5. Potentiometric surface of the Biscayne aquifer, November 3, 1969, during high water conditions.

tour maps. The shape of the water table, the hydraulic gradients, and the general direction of ground-water movement can be determined from the contours. The direction ground water moves is generally downgradient, perpendicular to the contour lines.

Figure 5 shows the configuration of the water table on November 3, 1969, when levels were the highest, seasonally. Rainfall at Fort Lauderdale in October was 15.68 inches and exceeded the average monthly rainfall, as shown in table 1, by 8.23 inches. Therefore, water levels in the aquifer were the highest of record. The absence of a depression in water levels in the well field indicates that pumping was affecting the configuration of the water table very little at the time. The general direction of ground-water outflow was to the ocean, Oleta River, and Snake Creek Canal.

Figure 6 shows the configuration of the water table on May 15, 1970, when water levels were low. No rainfall was recorded in the vicinity of Hallandale during May prior to the measurement, and less than the average monthly rainfall, shown in table 1, occurred at Fort Lauderdale during March and April. Therefore, water levels in the aquifer were extremely low. Although slight, the effects of municipal pumpage on the configuration of the water table during low-water conditions are more evident than during high-water conditions (fig. 5). Water levels in the well field were less than 0.2 foot lower than in the rest of the city. Water levels were less than 0.8 foot above mean sea level between the well field and the ocean. During low-water periods good management of the municipal water supply is especially important in helping to maintain fresh-water levels above sea level east of the well field and prevent sea-water intrusion. When fresh-water levels are lowered excessively, sea water tends to move inland into the aquifer. The contours in figure 6 indicate that the aquifer, especially in the southwest part of the city, is being recharged by Snake Creek Canal during low-water periods. Snake Creek Canal is approximately 2.0 miles south of the southwest corner of Hallandale.

Municipal pumpage in Hallandale is generally highest during the tourist season, which occurs during the months of little rainfall, as shown in figure 7. The increase in pumpage is owing primarily to an increase in the demand for municipally supplied water for domestic purposes and lawn sprinkling.

Figure 8 shows the configuration of the water table on October 19, 1970, when levels were intermediate. The contours in figure 8 seem to reveal virtually the same flow pattern as figures 5 and 6. Gradients in all three contour maps (figs. 5, 6 and 8) are nearly flat throughout the city and slope gently east of U.S. Highway 1. Municipal pumpage seems to have very little effect on the water table. The higher gradients in the western and southwestern parts of Hallandale during low-water conditions (fig. 6) indicate that the well field is being recharged by ground-water inflow from

Snake Creek Canal during the dry season. When the water level in the aquifer is high (fig. 5), water levels in Snake Creek Canal are regulated to aid in lowering water levels in the Hallandale area.

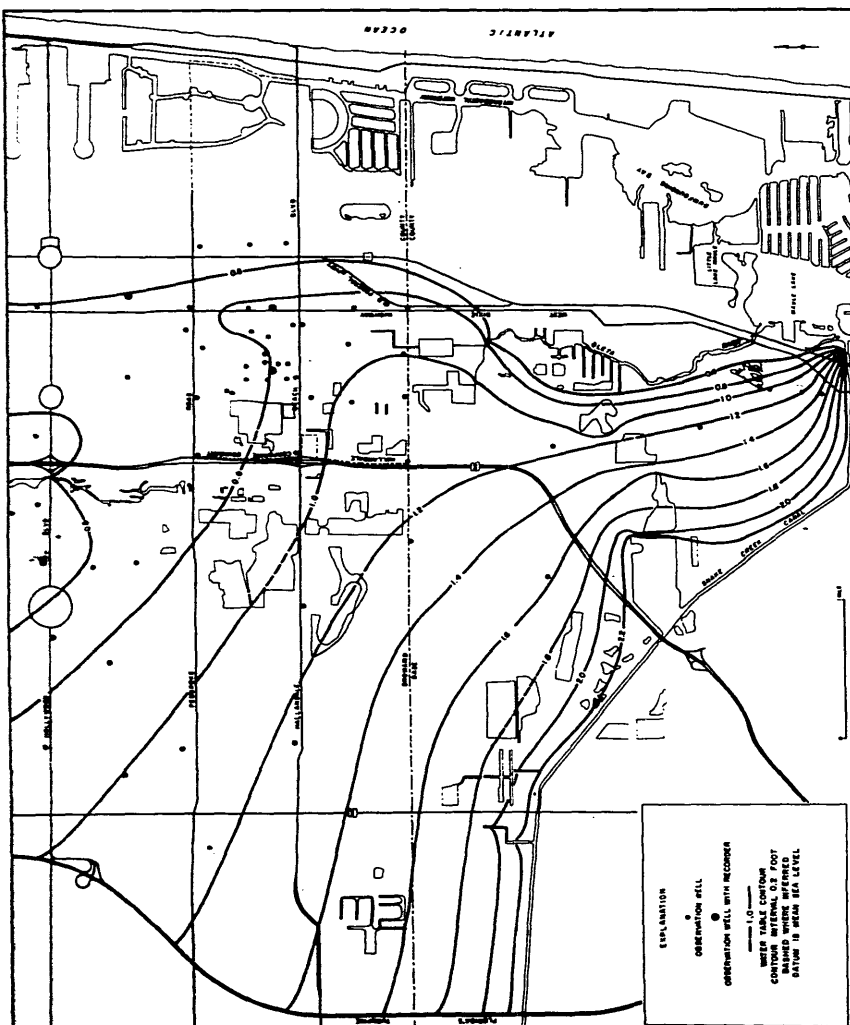

Figure 6. Potentiometric surface of the Biscayne aquifer, May 15, 1970, during low water conditions.

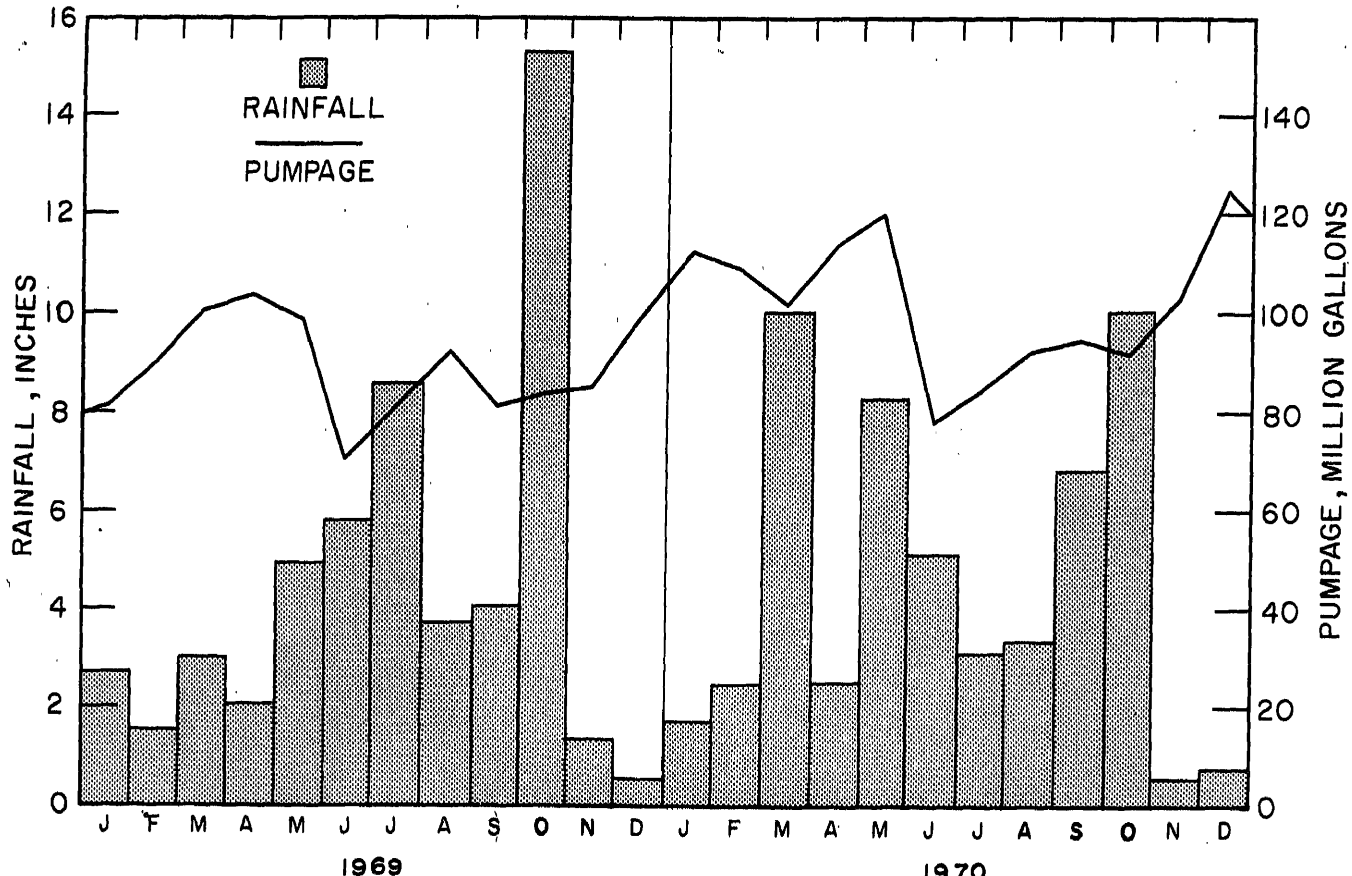

Figure 7. Monthly municipal pumpage at Hallandale and monthly rainfall at Dania, for 1969-70.

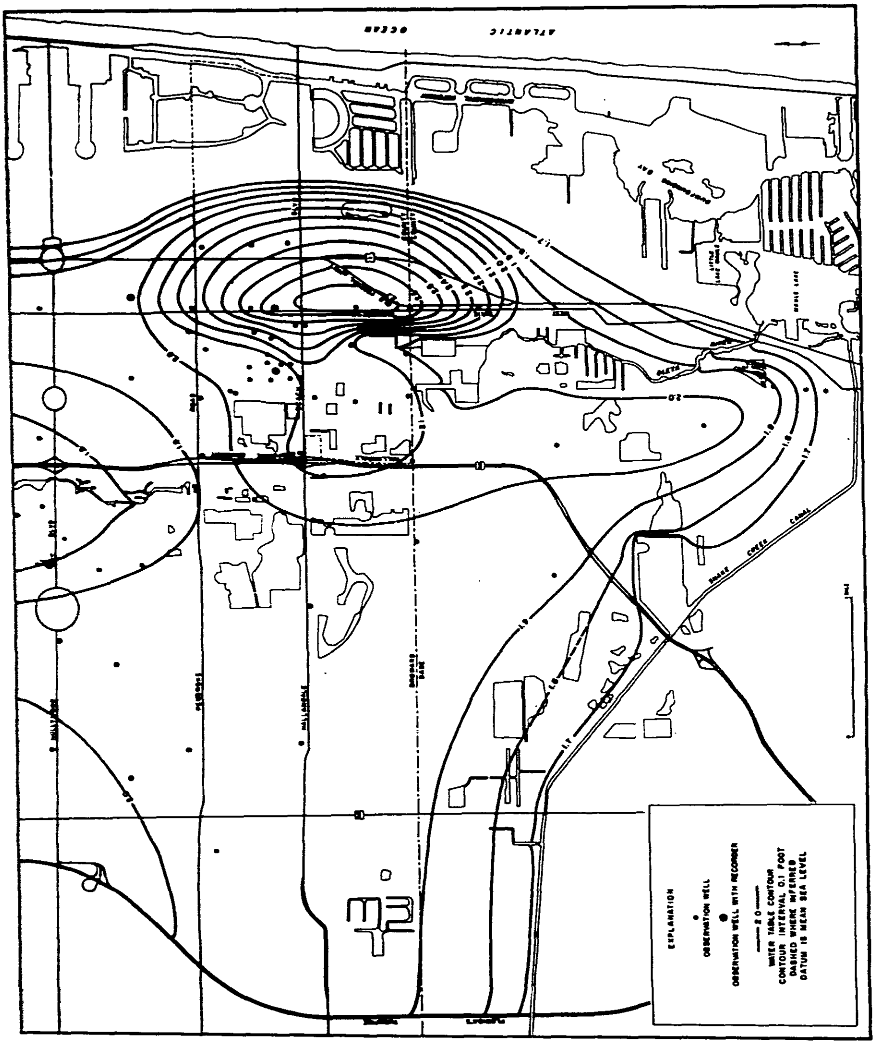

Figure 8. Potentiometric surface of the Biscayne aquifer, October 10, 1970, during intermediate water conditions.

HYDRAULIC PROPERTIES

Knowledge of the hydraulic properties of the Biscayne aquifer in Hallandale is essential to evaluate the ground-water potential of the area and to plan properly the expansion of municipal supplies. The principal properties of an aquifer are its capacities to transmit and store water, properties which are generally expressed as transmissivity and the storage coefficient.

Transmissivity (T) is the quantity of water that will flow through a vertical section of the aquifer 1 foot wide and extending the full saturated height, under unit hydraulic gradient, at the prevailing temperature of water (Theis, 1938, p. 892). The storage coefficient (S) is defined as the volume of water released from or taken into storage per unit surface area of the aquifer per unit change in the component of head normal to that surface. The most commonly used method for determining these properties is an aquifer test, in which a well penetrating the aquifer is pumped at a known rate and the resultant lowering of the water level in nearby non-pumped wells is observed.

Aquifer tests were made at the sites of wells in the Hallandale well field because they were the only large-volume wells available. Locations of supply wells and observation wells used in the aquifer test are shown in figure 9. Supply wells 1, 2 and 3 are 8-inch wells, 100 feet deep, cased to a depth of 85 feet, and screened and gravel packed from 85 to 100 feet. Supply wells 4, 5, and 6 are 12-inch wells, 65 feet deep, cased to a depth of 50 feet, with 15 feet of open hole. Observation well G-1473A is a 3-inch well, 96 feet deep, and cased to a depth of 93 feet, with 3 feet of open hole. Observation wells G-1400, G-1401 and G-1404 are 1¼-inch wells, 16 feet deep, cased to a depth of 14 feet, with a 2-foot sandpoint.

An aquifer test was made on June 3, 1971, when the water level in the aquifer was low. Before the test, supply wells 3, 4, and 6 were pumped for about 5 hours at 2,700 gpm (gallons per minute). Then all pumping was stopped for 3 hours, and the water-level recovery was observed in observation wells G-1400, G-1401, G-1404, and G-1473A (fig. 9). Water levels recovered 0.01 foot in all the observation wells during the 3-hour period.

At the end of the 3-hour period, when all pumping was stopped, supply wells 2, 3, and 4 were pumped at a rate (total) of 2,400 gpm for 7 hours. Water-level drawdowns were measured in well G-1473A, which is 61 feet from supply well 2, 57 feet from well 3, and 133 feet from well 4, by a continuous recording gage. Water levels were also measured during the test in the other observation wells shown in figure 9 to help determine the areal extent of the effects of pumping. Drawdowns of 0.05 foot were measured in wells G-1473A and G-1401 and 0.06 foot in wells G-1400 and G-1404. The water level in an observation well 0.22 mile southwest of the well field (well G-1192, fig. 1) declined 0.01 foot, and the level in a well 0.18 mile northwest of the well field (well G-1397, fig. 1) declined 0.04 foot.

The drawdowns were too small to permit computation of transmissivity and coefficient of storage by standard methods. The data indicated only that the aquifer is highly permeable and similar in character to the aquifer in the area of Norwood and Sunny Isles well fields of the city of North Miami Beach. Aquifer tests in that area by Leach and Sherwood (1963) indicated transmissivities ranging from 2.0 to 2.5 mgd per foot and storage coefficients ranging from 0.1 to 0.2.

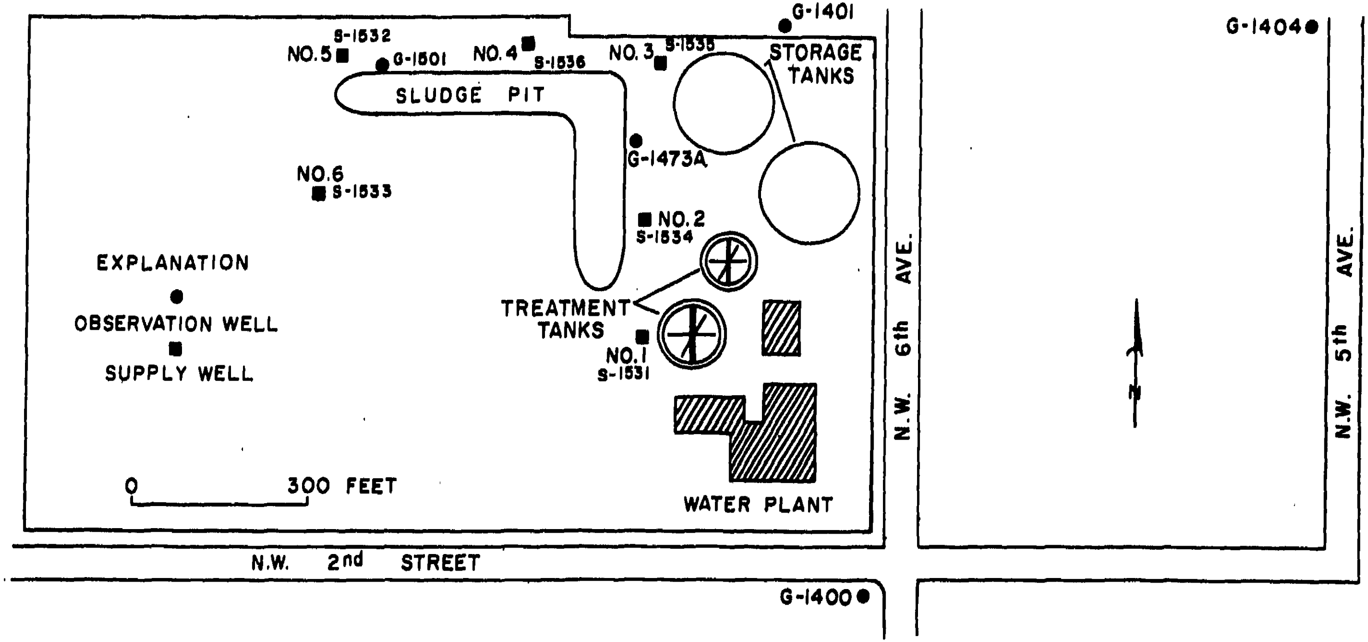

Figure 9. Locations of supply wells of the city of Hallandale and observation wells.

QUALITY OF WATER

GROUND WATER

The chemical quality of ground water in Hallandale, as in most of Broward County, is generally good. The quality varies somewhat because it is dependent upon constituents in the recharge water from canals draining inland areas and the composition of the aquifer materials.

Samples for water quality analysis were taken from municipal supply wells 1 (S-1531), 5 (S-1532), and 6 (S-1533) (fig. 9). Wells 5 and 6 are 65 feet deep, and well 1 is 100 feet deep. The chemical analyses of samples from these wells are shown in table 2. The quality is generally good on the basis of U.S. Public Health Service standards, as shown in table 3. The water is very hard, has high concentrations of iron and high color, but can be treated to meet standards recommended by the U.S. Public Health Service with little difficulty. The analyses show that only small amounts of detergents were in the water. Problems have arisen, however, because occasionally the concentration of detergents has been high, especially in well 5.

Iron in excessive amounts is a highly objectionable constituent in water intended for domestic use because of its appreciable effect on taste. It is also objectionable both in domestic use and in some industrial uses because it tends to leave a brownish stain. The U.S. Public Health Service recommends that water for public supply should not exceed 0.3 mg/l (milligrams per liter) iron. When used for lawn irrigation, water containing iron in excess of 0.3 mg/l may cause staining of buildings, sidewalks, and trees. The samples collected October 22, 1971, were also analyzed for iron content. Water from supply well No. 1 had the highest concentration, 0.5 mg/l (table 2). However, iron is substantially removed from the water by aeration and filtration at the Hallandale treatment plant.

Hardness is a term applied to the soap-neutralizing power of a water (McKee and Wolf, 1963, p. 195). It is attributable principally to calcium and magnesium and is expressed as an equivalent amount of calcium carbonate ($CaCO_3$). The calcium and magnesium are dissolved from limestone and shells in the aquifer. Hard water has no apparent harmful effects on man and is probably harmless. Water whose calcium carbonate concentration is in excess of 120 mg/l is considered hard. The calcium carbonate concentration of water from Hallandale's municipal wells ranged from 194 mg/l in well 6 to 279 mg/l in well 1. Hardness in water is objectionable because it consumes soap in laundry operations and forms incrustations in pipes, boilers, and plumbing fixtures.

Detergents in water are determined by the MBAS (methyl blue active substances) method, a method whereby all the active synthetic materials in a sample are measured by the total activated methyl blue and expressed

Table 2. Chemical analyses of raw water from Hallandale supply wells 1, 5, and 6.
(Chemical analayses, in milligrams per liter, except pH and Color)

Station	Date of Collection	Specific conductance (micromhos at 25° C (Kx10^6))	pH	Temperature (°C)	Color	Silica (SiO_2)	Iron (FE)	Arsenic (As)	Calcium (Ca)	Magnesium (Mg)	Strontium (Sr)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Alkalinity as $CaCO_3$	Hardness as $CaCO_3$		Dissolved Solids		MBAS
																				Calcium Magnesium	Non Carbonate	Residue at 180° C	Calculated	
Supply Well No. 1	10-20-70	570	8.3	—	10	6.0	—	—	99	2.9	0.86	18	2.1	284	40	26	0.3	2.2	239	260	21	348	341	0.07
	2- 9-71	620	8.0	25	20	5.8	—	—	106	3.2	.98	18	4.1	304	30	28	.4	5.1	249	279	30	364	352	.05
	5-14-71	600	8.3	—	25	5.3	—	—	104	2.6	1.00	20	3.4	296	29	32	.3	5.0	243	271	29	374	349	.05
	10-22-71	550	8.2	—	20	5.4	0.50	0.00	96	3.2	.86	19	0.4	272	26	30	.2	4.0	231	254	31	328	319	.02
Supply Well No. 5	10-20-70	555	8.3	—	5	5.6	—	—	86	3.2	.81	23	5.0	252	38	29	.3	2.5	213	229	16	334	321	.05
	2- 9-71	600	7.9	25	25	6.0	—	—	104	3.8	.94	16	3.9	312	23	28	.3	5.9	256	276	21	356	346	.07
	5-14-71	600	8.2	—	25	5.7	—	—	104	3.8	1.00	19	3.6	296	25	29	.4	8.4	243	276	34	370	346	.03
	10-22-71	600	7.9	—	40	5.4	.39	.00	98	3.6	.84	19	4.0	284	28	32	.3	—	233	261	28	334	331	.07
Supply Well No. 6	10-20-70	454	8.5	—	0	5.2	—	—	72	3.1	.79	18	4.0	184	35	27	.4	3.6	164	194	29	272	268	.06
	2- 9-71	600	7.9	—	25	6.0	—	—	104	3.4	.92	17	4.2	308	22	29	.4	7.2	253	272	22	356	346	.07
	5-14-71	590	8.2	—	25	5.6	—	—	104	3.2	1.00	20	4.0	296	26	31	.4	9.9	243	274	31	358	351	.04
	10-22-71	600	7.9	—	30	5.4	.46	.10	98	3.6	.85	19	4.0	284	27	30	.2	6.4	233	261	28	354	334	.02

in milligrams per liter (MBAS-mg/1). Difficulties caused by detergents in domestic water include foaming, turbidity, interference with coagulation, and production of taste and odor. The MBAS concentrations in the samples analyzed (table 2) ranged from 0.05 to 0.07 mg/1 and do not exceed the limit of 0.5 mg/l recommended by the U.S. Public Health Service. However, as much as 3.22 mg/l MBAS has occurred several times in water from wells, but for only a few days at a time. The major problem arising from the high detergent levels has been the difficulty in treating the water.

Studies were made to determine the source of detergents. Water from nine private wells in the vicinity of the well field was tested for detergents, as shown in figure 10. Six of the samples contained no MBAS, and the other three contained only 0.01 mg/1, as shown in table 4.

The sludge from the treatment process at the Hallandale water plant is dumped into a pit about 10 feet deep in the center of the well field (fig. 10).

Table 3. U.S. Public Health Service Drinking Water Standards

Characteristic	Limit Not to Be Exceeded	Cause for Rejection
PHYSICAL		
Color	15 units	
Taste	Unobjectionable	
Threshold odor number	3	
Turbidity	5 units	
CHEMICAL	mg/l	mg/l
Alkyl benzene sulfonate	0.5	
Arsenic	0.01	0.05
Barium		1.0
Cadmium		
Chloride	250	
Chromium (hexavalent)		0.05
Copper	1	
Carbon chloroform extract*	0.2	
Cyanide	0.01	0.2
Fluoride†	0.7-1.2	1.4-2.4
Iron	0.3	
Lead	0.05	
Manganese	0.05	
Nitrate	45	
Phenols	0.001	
Selenium		0.01
Silver		0.05
Sulfate	250	
Total dissolved solids	500	
Zinc	5	

*Organic contaminants.

†The concentration of fluoride should be between 0.6 and 1.7 mg/l, depending on the listed and average maximum daily air temperatures.

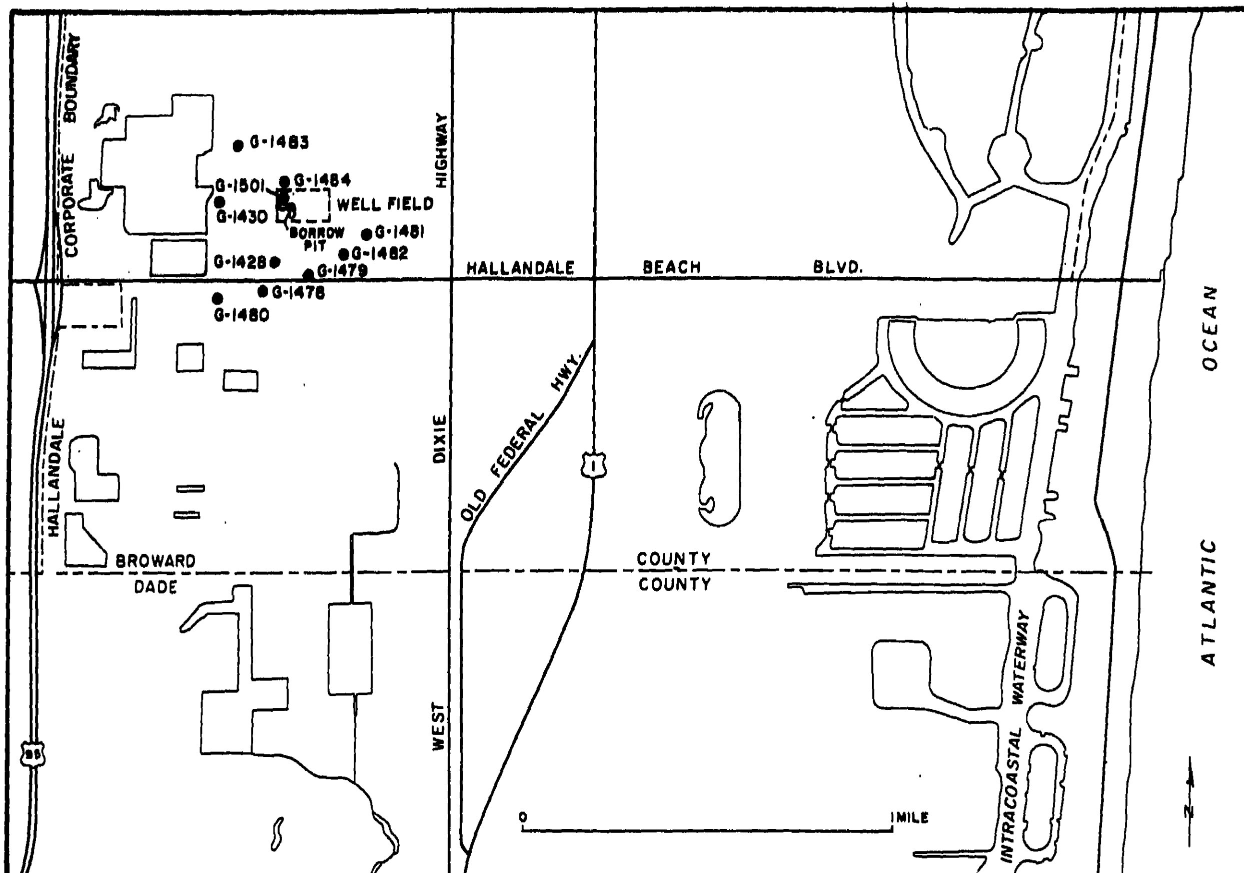

Figure 10. Location of wells sampled for MBAS analysis.

Table 4. MBAS concentration in wells sampled in the Hallandale well field area, January 22, 1970.

Well No.	Depth (ft.)	MBAS (mg/l)
G-1428	28.0	0.00
G-1430	75.0	.01
G-1478	—	.00
G-1479	40.0	.00
G-1480	—	.00
G-1481	22.0	.01
G-1482	—	.00
G-1483	25.2	.01
G-1484	—	.00

A 20-foot test well, G-1501, 2 feet north of the pit, penetrates the first layer of limestone below the bottom of the pit. Water from the well was analyzed for MBAS to determine whether the pit was a source of contamination. The concentration of MBAS was extremely low (0.01 mg/l).

SURFACE WATER

There are several small lakes in Hallandale and a large borrow pit (fig. 1) 0.25 mile west of the well field. The chemical quality of the water in the lakes and the pit is generally good.

Because the borrow pit is operational, the water standing in it was sampled regularly and the water analyzed for major chemical constituents and several trace constituents useful in detecting possible man-made contaminants. Results of the analysis are shown in table 5. The water is similar in character to other surface water in the area, except for a high turbidity of 788 JTU (Jackson turbidity units). Traces of constituents such as nitrate, phosphate, and phenols, shown in the analysis are well within the limits recommended by the U. S. Public Health Service for public water supply.

SEA-WATER INTRUSION

Sea water can enter the Biscayne aquifer by 1) direct intrusion into the coastal parts of the aquifer and above uncontrolled canals and 2) upward movement of sea water that infiltrated the beds below the Biscayne aquifer during Pleistocene interglacial stages (McCoy 1970 p. 33). In the Hallandale area, direct intrusion is the more common. The movement of sea water into the Biscayne aquifer is governed by the height of the fresh-water levels above mean sea level. Because sea water is slightly heavier than fresh water, it moves inland in the aquifer in a wedge shape until balanced by sufficient fresh-water head. The greatest inland extent occurs at the base of

Table 5A. Chemical analyses of water from the borrow pit west of the Hallandale well-field.
(Chemical analyses, in milligrams per liter, except pH and color)

Date of Collection	Specific conductance in Micromhos at 25°C (Kx10⁶)	pH	Temperature (°C)	Color	Turbidity	Silica (SiO_2)	Iron (Fe)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)	Strontium (Sr)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)
2-14-69	380	7.9	25	5	788	3.3	0.00	0.00	56	4.0	—	17	5.2	172	22	28	0.3	1.2
2- 9-71	525	8.3	19	0	55	4.9	.01	.00	82	4.6	1.2	17	5.9	168	87	23	2.0	2.0
9-28-71	480	6.5	30	0	50	5.6	.00	.00	70	4.9	1.1	18	5.2	154	82	24	0.2	2.1
2- 4-72	551	8.1	—	10	30	7.3	.03	—	84	5.5	1.3	19	5.7	184	90	24	0.3	0.0

Date of Collection	Hardness as $CaCO_3$		Dissolved Solids		Aluminum (Al)	Zinc (Zn)	Lead (Pb)	Copper (Cu)	Chromium (Cr)	Arsenic (As)	Ammonium (NH_4)	N-Organic	Nitrite (NO_2)	Phenols	Oil and Grease	MABS	Ortho Phosphate (PO_4)	Total Phosphate (PO_4)	Alkalinity as $CaCO_3$
	Calcium Magnesium	Non Carbonate	Residue at 180°C	Calculated															
2-14-69	156	15	227	222	0.00	0.00	0.02	0.00	0.00	—	0.02	0.09	0.03	0.001	—	—	0.03	0.06	141
2- 9-71	220	80	330	319	.00	.03	.00	.00	.00	0.03	.03	0.17	.02	—	3.0	0.01	.00	.08	138
9-28-71	—	—	—	289	—	.01	.001	.01	.00	—	.06	4.2	.02	—	8.2	—	.02	.05	—
2- 4-72	230	83	352	328	—	.05	.005	.00	.00	.00	.06	0.3	.02	—	—	.10	.01	.01	151

Table 5B. **Pesticide analyses of water from the borrow pit west of the Hallandale well field.**
(Chemical analyses, in micrograms per liter, except organic carbon, in milligrams per liter)

Date & Time	Aldrin	DDD	DDE	DDT	Dieldrin	Endrin	Heptachlor	Lindane	2,4-D	2,4,5,-T	Silvex	1/ Organic Carbon	Diazinon	Ethion	Malathion	Methyl-Parathion	Methyl-Trithion	Parathion	Trithion
2-9-71 0915	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2	—	—	—	—	—	—	—
7-27-71 0750	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	7	—	—	—	—	—	—	—
2-4-72 1600	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.04	14	0.00	0.00	0.00	0.00	0.00	0.00	0.00

the aquifer. Consequently, when fresh-water levels in the aquifer are high, the sea water is held near the coast, but, when fresh-water levels in the aquifer are low, the sea water moves inland into the aquifer.

According to the Ghyben-Herzberg principle (Brown, 1925, p. 16-17), if a specific gravity of 1.025 is assumed for sea water, each foot of fresh water above mean sea level should indicate 40 feet of fresh water below mean sea level. The basic premise of the Ghyben-Herzberg principle is that the position of the interface between fresh water and salt water in a coastal aquifer is governed by a hydrostatic equilibrium between fresh water and the more dense sea water. However, Kohout (1960, p. 2133-2141) showed that the salt-water front in the Biscayne aquifer along the coast in the Miami area, is dynamically stable at a position seaward of that computed according to the Ghyben-Herzberg principle.

The extent of sea-water intrusion into the aquifer was determined by analyzing water samples from pumping wells for chloride content, because about 91 percent of the dissolved constituents in sea water are chloride salts. Figure 11 shows the chloride content of water in private, municipal, and U.S. Geological Survey wells in the Hallandale area as of May 1969. The high chloride content in water from wells east of West Dixie Highway is owing to sea-water intrusion. The high chloride content of water from well G-892 (7,000 mg/l) is owing to sea-water intrusion from the salty Oleta River.

Contamination of fresh-water supplies in Hallandale by sea-water intrusion has been a long-standing threat. The well field is 2.0 miles west of the Intracoastal Waterway, the closest source of contamination. Four salinity test wells, G-1432, G-1433, G-1434, and G-1435, were drilled in a line (fig. 1) between the Intracoastal Waterway and the well field to monitor the salt front. The wells were drilled deep enough to intercept the salt-water-fresh-water interface. Information from the drilling of these wells was used in constructing an east-west section through Hallandale. This section, as shown in figure 12, shows the salt front during low and moderately high water levels. The toe of the salt front is located between well G-1434, 0.45 mile east of the well field, and well G-1435, 0.2 mile east of the well field.

Because water levels in the aquifer in the vicinity of the well field were as low as 0.8 foot above sea level (fig. 6) and the toe of the salt front (fig. 12) was estimated to be 0.3 mile east of the well field, any new well-field would be less liable to salt-water intrusion if it were west of the present site. Large withdrawals of fresh water from the aquifer and subsequent lowering of the fresh-water head could cause the salt front to move farther inland.

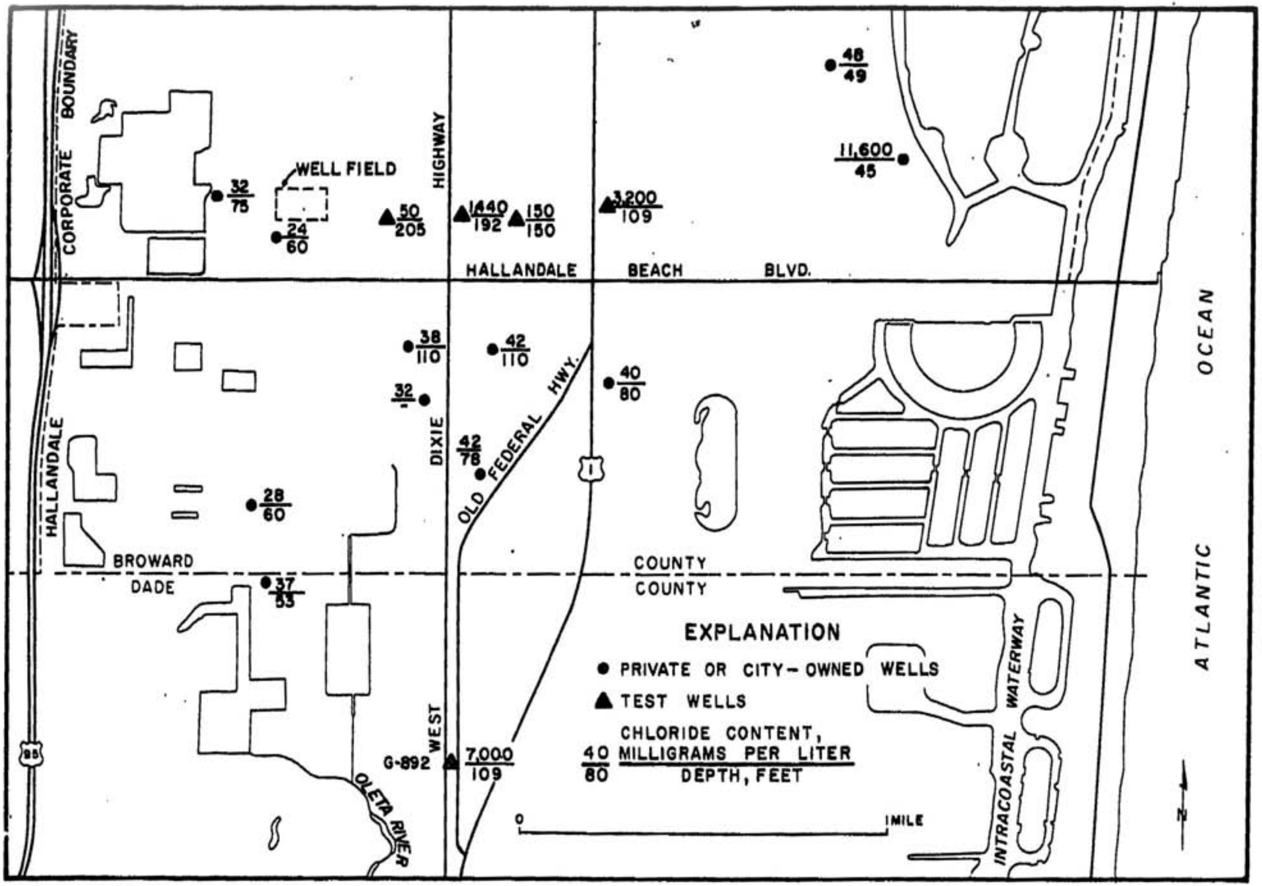

Figure 11. Chloride content of water from selected wells sampled in May 1969.

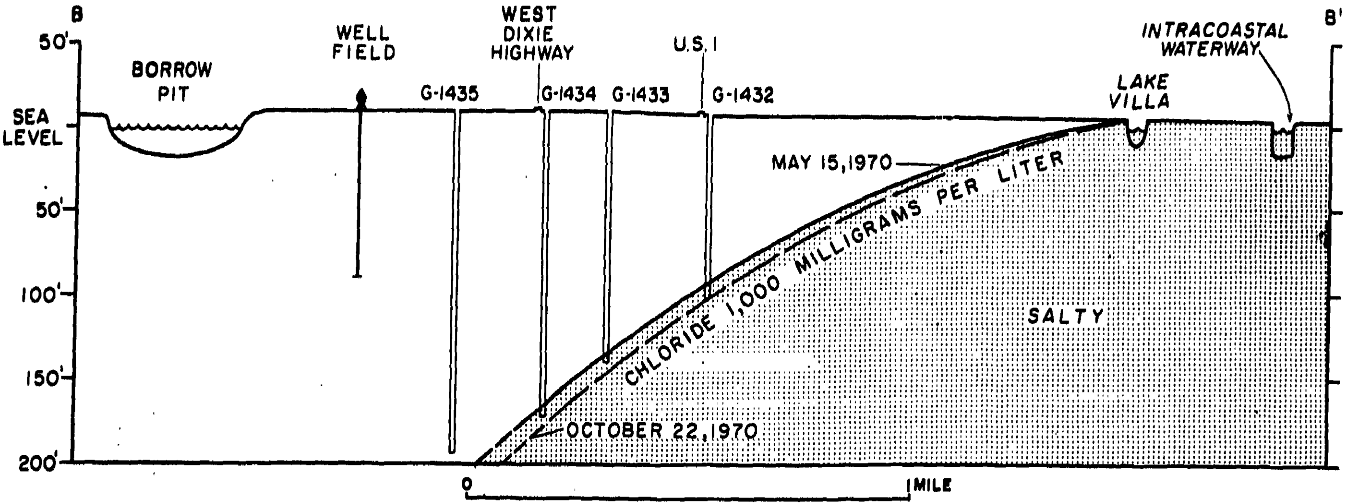

Figure 12. East-west section (B-B', fig. 1) through the Hallandale well-field area showing the inland extent of salt-water intrusion, October 22, 1969, during moderately high water levels, and May 15, 1970, during low water levels.

WATER USE AND SUPPLY

Water for public, domestic, irrigation, and industrial use in Hallandale is supplied by wells tapping the Biscayne aquifer. In the city, municipal pumpage constitutes by far the greatest withdrawal. It includes all public, most of the domestic and industrial, and some irrigation use. A few small industries and some private homes are self-supplied, but the pumpage for these is insignificant. Numerous private wells (1- to 2-inch diameter), used for watering lawns, tap the 20- to 30-foot zone.

Hallandale's municipal supply is obtained from six wells (fig. 9) that have a combined design capacity of 8.6 mgd. The city's water-treatment plant has a design capacity of 7.2 mgd. Therefore, at present (1971), the capacity of the water-treatment plant limits the quantity of water that can be delivered to the city's mains. Supply well 7, (fig. 1) in the northwest part of Hallandale, has a design capacity of 3 mgd (2,100 gpm). It is not yet operational. Supply wells 1, 2, and 3 are 8 inches in diameter and 100 feet deep. They are cased to 85 feet and are screened and gravel packed from 85 to 100 feet. The average yield from each of these wells is 1,600 gpm. Supply wells 4, 5, and 6 are 12 inches in diameter, 65 feet deep, and are cased to a depth of 50 feet and open-hole from 50 to 65 feet. The average yield from each of these wells is 1,100 gpm. Supply well 7 is 88 feet deep, cased to a depth of 70 feet, and open-hole below 70 feet.

On the average in 1970, 3.36 mgd was pumped from the Hallandale well field, and the peak day pumpage was approximately 7.2 mg, the capacity of the treatment plant. During dry periods when water levels in the aquifer are low, yield from the wells decreases. Generally, the wells are pumped the most in December - May, as these months include both the tourist and dry seasons.

Expanding the capacity of both the well field and water-treatment plant would provide additional water to meet the demands of the near future. For example, if population and water demand increase beyond 1970 at the same rate that they increased from 1961 to 1970, the population will be 40,000 and the monthly pumpage will be 198 mg (6.5 mgd) at the end of 1980, as shown in figure 13. The 6.5 mgd would be 193 percent of the current average daily pumpage, and, of course, the peak daily pumpage during the tourist and dry season would greatly exceed 7.2 mg.

SUMMARY

The city of Hallandale has an area of about 4 square miles bordering the ocean in southeastern Florida and in 1970 had a population of more than 24,000. Water for all purposes in Hallandale is provided by the highly per-

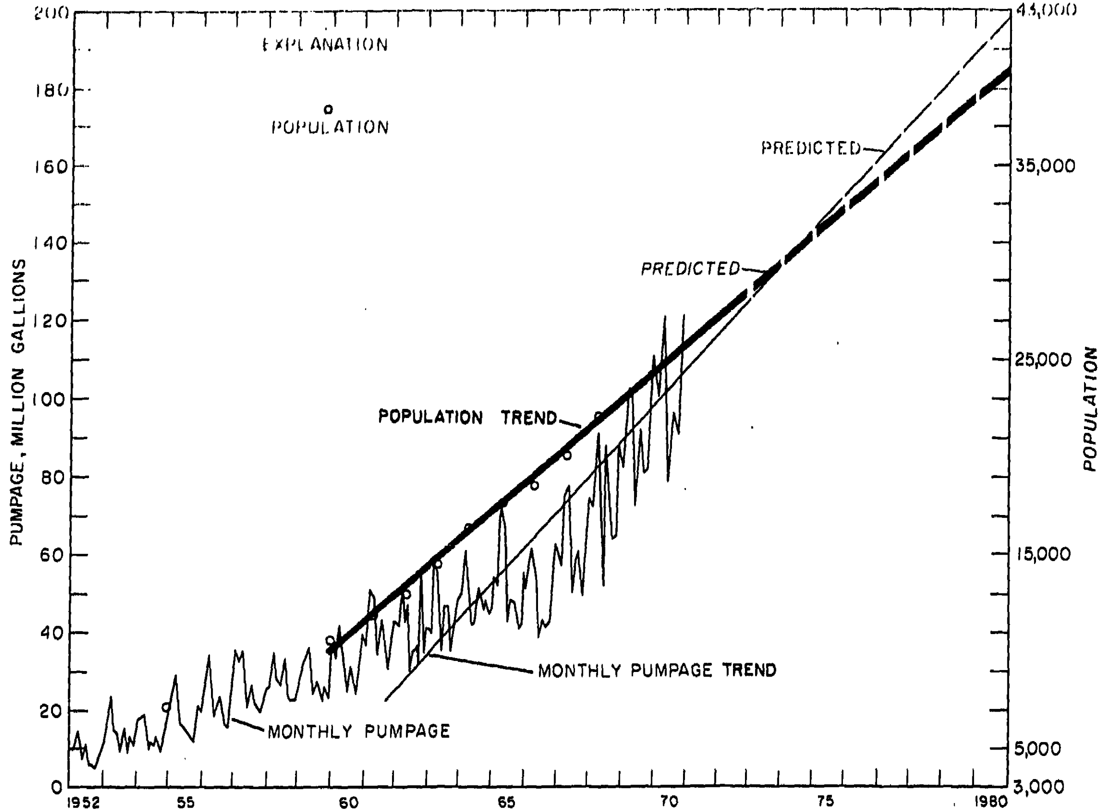

Figure 13. Population and monthly municipal pumpage for 1952-70 and projected population and monthly pumpage through 1980.

meable Biscayne aquifer, which is an excellent source of water. However, the permeable nature of the aquifer also permits the inland intrusion of sea water and the infiltration of urban and industrial contaminants. The aquifer is composed chiefly of permeable limestone, sandstone, and sand that extends from land surface to a depth of approximately 200 feet. The major source of recharge to the aquifer is rain that infiltrates to the water table. Consequently water levels in the aquifer are high during periods of high rainfall and low during periods of little rainfall.

The configuration of the water table is greatly influenced by the Intracoastal Waterway, the Oleta River, Snake Creek Canal, and municipal pumping. The water-level data indicate that the effect from municipal pumping is relatively small. The water-level gradient is gentle; east of the ridge area it is seaward, to the southeast it is toward the Oleta River, and to the southwest it is toward Snake Creek Canal.

Gradients west of the ridge area are nearly flat. During low-water periods, the well field is being recharged by inflow from Snake Creek Canal. During high-water periods, water levels in Snake Creek Canal are regulated to aid in lowering water levels in the Hallandale area.

Pumping-test data indicate that large quantities of water are available from the Biscayne aquifer in the area. The test data indicate that the aquifer is similar in character to the aquifer in the vicinity of the well fields in the city of North Miami Beach, where the transmissivity of the aquifer ranges from 2.0 to 2.5 mgd per ft.

The chemical quality of the ground water is generally good. The water is relatively hard, and the iron content is high.

Sea-water contamination of fresh-water supplies in Hallandale has been a long standing threat. The well field is 2.0 miles west of the Intracoastal Waterway, which is connected to the ocean. The salt front has moved inland, by direct intrusion of sea water, to 0.3 miles east of the well field. Fresh-water levels maintained a reasonable distance above sea level would help to keep the salt water from moving farther inland into the aquifer. During low-water periods, the fresh-water level has been less than 0.8 foot above sea level in the vicinity of the well field. During critical dry periods, good management of the fresh water supplies is important in helping to keep salt water from moving farther inland.

Providing an adequate municipal supply and safeguarding this supply against salt-water intrusion and man-made contaminants are major water problems confronting Hallandale. Developing new, additional supplies in the southwest part of Hallandale would safeguard against salt-water intrusion and would utilize the recharge from Snake Creek Canal during low-water periods. Drilling a series of test wells in the southwest part of the city would allow a determination of the aquifer's potential for yield and the quality of ground water as well as the location of the salt front.

WELL NUMBERS

In order to coordinate data from wells on a nationwide basis, the U.S. Geological Survey has adopted a well-location number system, which locates the well by a 16-digit number based on latitude and longitude. The consecutive county wells numbers used in this report are referred to the nationwide system, as follows:

County No.	Latitude-Longitude No.
G 892	255800N0800852.1
G 1192	255907N0800923.1
G 1241	255948N0800909.1
G 1397	255925N0800924.1
G 1400	255914N0800917.1
G 1401	255921N0800917.1
G 1404	255919N0800912.1
G 1428	255912N0800923.1
G 1430	255917N0800932.1
G 1432	255917N0800832.1
G 1433	255916N0800845.1
G 1434	255916N0800853.1
G 1435	255916N0800904.1
G 1472	255916N0800854.1
G 1473	255918N0800918.1
G 1473A	255918N0800918.2
G 1478	255905N0800924.1
G 1479	255907N0800917.1
G 1480	255903N0800931.1
G 1481	255913N0800908.1
G 1482	255910N0800912.1
G 1483	255925N0800928.1
G 1484	255921N0800922.1
G 1501	255918N0800919.1
S 1531	255917N0800917.1
S 1532	255919N0800919.1
S 1533	255918N0800920.1
S 1534	255918N0800917.1
S 1535	255919N0800917.1
S 1536	255919N0800918.1
S 1537	255940N0800929.1

REFERENCES

Brown, J. S.
1925 *A study of coastal water, with special reference to Connecticut:* U. S. Geol. Survey Water-Supply Paper 537, 101 p.

Cooke, C. W., and Mossom, Stuart
1929 *Geology of Florida:* Florida Geol. Survey 20th Ann. Rept. p. 29-227, 29 pl. geol. map.

Cooke, C. W., and Parker, G. G.
1945 *Geology of Florida:* Florida Geol. Survey Bull. 29.

Grantham, R. G., and Sherwood, C. B.
1968 *Chemical quality of waters of Broward County, Florida:* Florida Div. Geology Rept. Inv. 51, 52 p.

Kohout, F. A.
1960 *Cyclic flow of salt water in the Biscayne aquifer of southeastern Florida:* Jour. Geophys. Research, v. 65, no. 7, p. 2133-2141.

Leach, S. D. and Sherwood, C. B.
1963 *Hydrologic studies in the Snake Creek Canal area, Dade County, Florida:* Florida Geol. Survey Rept. Inv. 24, 33 p.

McCoy, H. J., and Hardee, Jack
1970 *Ground-water resources of the lower Hillsboro Canal area, southeastern Florida:* Florida Dept. Natural Resources, Bureau of Geology, Rept. Inv. 55, 44 p.

McKee, J. E. and Wolf, H. W.
1963 *Water quality criteria:* California Water Quality Control Board Pub. 3-A, p. 391.

Meinzer, O. E.
1923 *The occurrence of ground water in the United States, with a discussion of principals:* U. S. Geol. Survey Water Supply Paper 489, 321 p.

Parker, G. G., and Cooke, C. W.
1945 *Late Cenozic geology of southern Florida, with discussion of the ground water:* Florida Geol. Survey Bull. 27, 119 p.

Parker, G. G., Ferguson, G. E., Love, S. K. and others
1955 *Water resources of southeastern Florida, with special reference to the geology and ground water of the Miami area:* U. S. Geol. Survey Water Supply Paper 1255, 965 p.

Sanford, Samuel, and Matson, G. C.
1909 *The topography and geology of southern Florida:* Florida Geol. Survey 2nd Ann. Rept., p. 175-231.

Sherwood, C. B., Jr.
1959 *Ground water resources of the Oakland Park area of eastern Broward County, Florida:* Florida Geol. Survey Rept. Inv. 20, 40 p.

Sherwood, C. B., and Grantham, R. G.
1965 *Water control vs. sea-water intrusion, Broward County, Florida:* Florida Geol. Survey Leaflet 5, 13, p.

Schroeder, M. C., Klein, Howard, and Hoy, N. D.
1958 *Biscayne aquifer of Dade and Broward Counties, Florida:* Florida Geol. Survey Rept. Inv. 17, 56 p.

Tarver, G. R.
1964 *Hydrology of the Biscayne aquifer in the Pompano Beach area, Broward County, Florida:* Florida Geol. Survey Rept. Inv. 36, 48 p.

Theis, C. V.
1938 *The significance and nature of the cone of depression in ground-water bodies:* Econ. Geology, v. 33, no. 8, p. 889-902.

U. S. Public Health Service
1962 *Public Health Service drinking water standards:* U. S. Dept. Health, Education and Welfare, Public Health Service Pub. 956, 61 p.

U. S. Dept. of Commerce
Climatological Data: Florida Annual Summaries.